AN APPRAISAL OF QUATERNARY CALCIUM CARBONATE DEPOSITS IN CORNWALL

F.M.P. HOWIE[1] *AND P.J. EALEY*[2]

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Cornwall's calcium carbonate-rich deposits consist predominantly of coastal Holocene beaches, beachrock, dunes, eolianites, tufa and speleothems, offshore coastal maërl beds and late Pleistocene littoral deposits. The majority of these calcareous deposits in Cornwall, with the exception of some tufas and speleothems, were clearly not derived from within Cornwall itself but are largely the product of a regional offshore north-east Atlantic $CaCO_3$ budget controlled by cyclical marine transgressions and regressions coupled with local climate factors operating during the Quaternary.

[1] *29 Pendarves Road, Penzance, Cornwall, TR18 2AJ, U.K.*
[2] *8 Minster Fields, Manaccan, Helston, Cornwall, TR12 6JG. U.K.*
(E-mail: fmp-howie@msn.com).

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INTRODUCTION

The Quaternary calcareous deposits of Cornwall seem first to have attracted the attention of Borlase (1758), who attributed the widespread occurrence of acid soluble 'spar' in freestones around Newquay to marine influences and described the stalactitic cave deposits in Holywell Bay. Paris (1818) subsequently attributed the transformation of recent beach and dune sands into sandstones to impregnation by percolating solutions of calcium carbonate derived from on-shore shelly deposits. At this time recent cemented sandstones, tufa, and speleothems appear to have been regarded as the same phenomenon.

Little had been published on the mineralogy and geochemistry of Quaternary calcareous deposits in Cornwall before the work on the modern beach and dune sands of south-west England, undertaken by Merefield between 1981 and 1989, recognized the significance of the area for the study of temperate littoral carbonate sand accumulation. Earlier, valuable information on the processes involved in the carbonate cementation of recent beach sands in the UK, primarily in Cornwall, was contained in unpublished work by West (1970) who also provided analytical data on the diagenesis of the calcareous raised beach deposits in south-west England (West, 1973). Finally, detailed work was undertaken on the nature and origin of Quaternary palaeokarsts in south-west England by Morawiecka (See Pazdur *et al*., 1995). In this paper the distribution of these calcareous coastal deposits is described and their inter-relationships discussed.

GEOGRAPHICAL AND GEOLOGICAL SETTING

Cornwall's calcium carbonate-rich on-shore deposits consist of extensive Holocene beaches and dunes, many of which are composed primarily of calcareous skeletal/shell sand (locations shown in Figure 1), tufa and speleothems and calcite-cemented beachrock (locations shown in Figure 2). Calcareous Pleistocene littoral deposits (raised beach and dune), known locally as 'sandrock', are limited to the north Cornish coast at Godrevy, Fistral and Trebetherick. Extensive offshore live and dead coralline red algae maërl beds, the oldest of mid-Holocene age, are associated with the Fal and Helford estuaries in Falmouth Bay.

Surface outcrops of pre-Quaternary calcareous deposits in mainland Cornwall are relatively rare apart from sporadic Devonian limestones and calcareous mudstones near Launceston, Newquay, Perranporth, Trevone (Padstow), Veryan (Selwood *et al*., 1999) and Saltash (Leveridge *et al*., 2002). However, on the off-shore platform to the west, north (Western Approaches) and the south (Western English Channel) of the Cornubian Massif (Palaeozoic basement) extensive Upper Cretaceous chalk deposits and Tertiary carbonates (Jones and Cockburn formations) are either exposed on the inner continental shelf, as shown in Figure 3, or covered by thin late Quaternary deposits, sand patches and sheets themselves of highly calcareous, mainly shelly sands and gravels of Quaternary age (Evans, 1990).

COASTAL CARBONATE-RICH DEPOSITS

Beach sands

As part of the preparation of the first generation of the Cornwall and Isles of Scilly Shoreline Draft Management Plans (SMP1), published in 1997/1998 as Shoreline Management Plans: South Cornwall - Rames Head to Lizard Point, Lizard Point to Lands End and North Cornwall - Land's End to Hartland Point (CISCAG, 2009), seventy beaches were sampled for their quartz, lithic and carbonate content. The beach sand carbonate and combined lithics plus quartz fraction data from this survey, augmented with data reported earlier by Merefield (1981, 1984), is shown in Figure 4. The calcium carbonate content of the beach sands along several stretches of the Cornish coast, totalling some 40 km, exceeds 50% (locations and percentages of $CaCO_3$ mapped in Figure 1 and plotted in Figure 4). Data on beach carbonate from CISCAG (2009) and Merefield (1981, 1984) indicates these Cornish beaches, together with those of

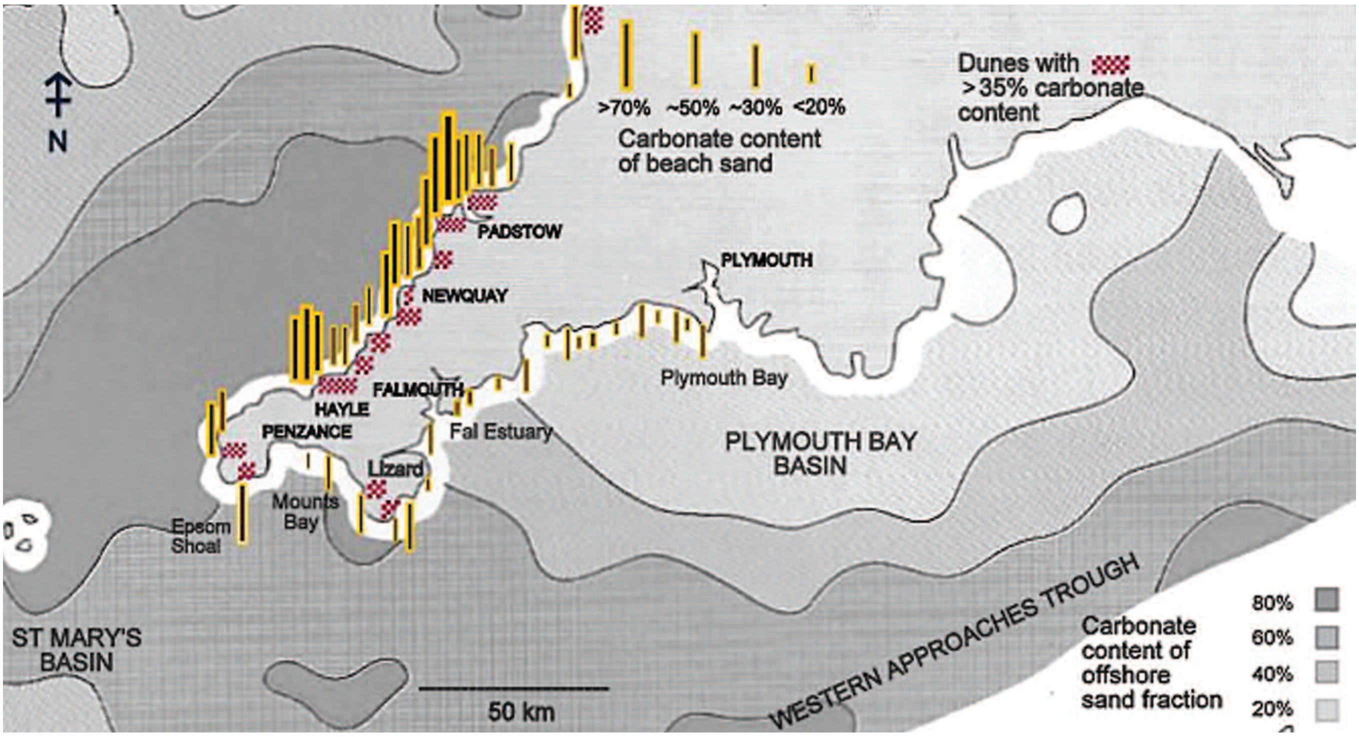

Figure 1. *Map showing relationship between %CaCO$_3$ content of offshore Quaternary sediments (shaded grey), beach sand %CaCO$_3$ (yellow bars) and high carbonate dunes (red stippled areas) along Cornish coastline. Map adapted from Evans (1990, figure 50), beach carbonate data from SMP1 (CISCAG, 2009) and Merefield (1981, 1984), dune carbonate from DEFRA (2007, Table 3.10).*

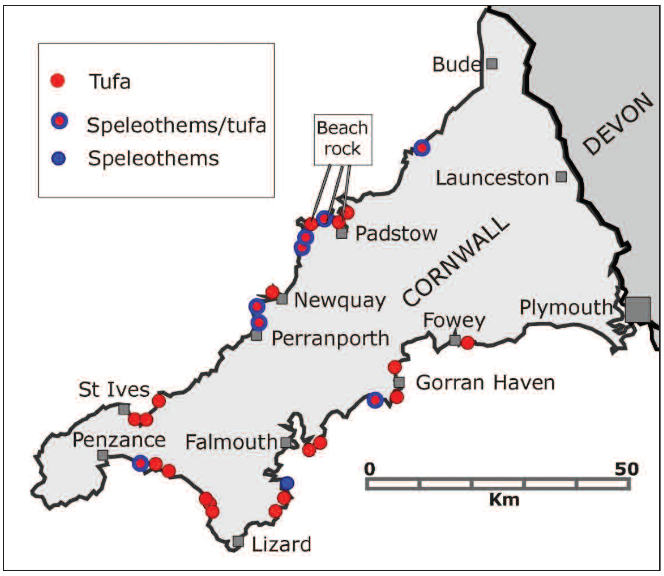

Figure 2. *Map showing location of currently recognised tufa, speleothem and beachrock deposits around the Cornwall coast.*

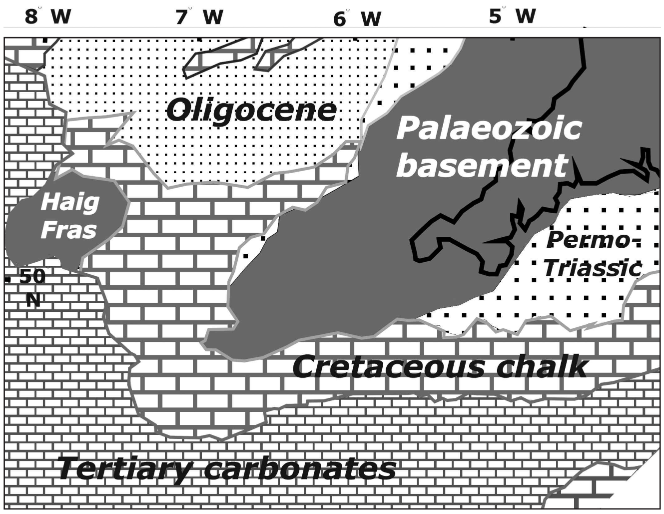

Figure 3. *Map showing offshore carbonate distribution - adapted and simplified after Evans (1990).*

South Pembrokeshire contain the highest calcium carbonate content in England and Wales (May and Hansom, 2003) and rank alongside the high (≥50%) calcium carbonate content beaches on the coasts of the Western Islands, Orkney and Strathclyde (Ritchie and Mather, 1984).

The highest carbonate fraction sands (range 15-90%: average ~52%) are reported from beaches between Bude (Crooklets) and Godrevy in North Cornwall and around Land's End and the Lizard to Mullion in West Cornwall (Figure 4). Between Coverack and Saltash in South Cornwall the carbonate fraction is significantly lower (range 5-50%: average ~16%; see Figure 4). Analyses of those Cornish beach sands with total carbonate content above ~30% reveals that the average low-Mg + high-Mg calcite to aragonite ratio is ~1:0.75 (Merefield, 1981, 1984). Merefield's (1981, 1984) data also indicates that aragonite and high-Mg calcite content tends to increases westwards along both the north and south coasts of the south-west peninsula. Merefield (1984) concluded that the carbonate content of beach sand is controlled by high energy on- and off-shore wave action on the large populations of calcareous (skeletal) biota produced as a result of the wide tidal ranges and availability of rocky littoral and sub-littoral zones. The proportions of low-Mg and high Mg calcite and aragonite reflect the cool temperate marine biota occurring around the south-west peninsula (e.g. low-Mg calcite-rich *Mytilidae*, aragonite-rich *Cardiidae* and high-Mg calcite rich *Balanus spp*., echinoderms and coralline red algae). There appears to be a westward increase in the proportion of aragonite in sands along the north and south of the south-west peninsula. The effect of eroding local cliff lithologies and input of terrigenous sediment input increases lithic and quartz beach

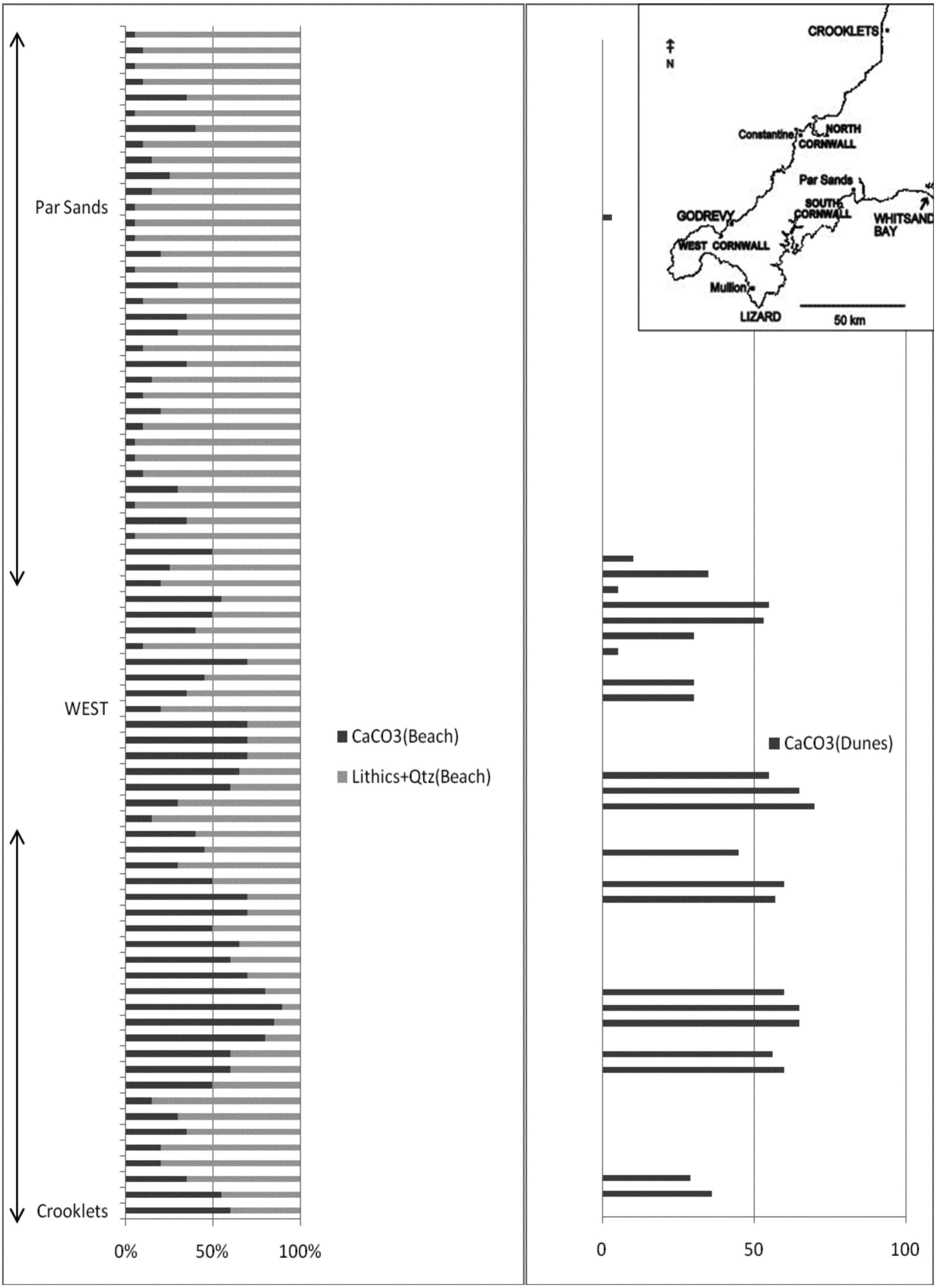

Figure 4. *Histograms illustrating the distribution of %$CaCO_3$ and lithics plus quartz fractions of beach and dune sands around the South, West and North Cornwall coasts (see inset map). Beach carbonate and lithics plus quartz data from SMP1 (CISCAG, 2009) and Merefield (1981, 1984), dune carbonate from DEFRA (2007, Table 3.10).*

sand fraction eastwards along both the north and south coasts of the south-west peninsula as revealed by data in Merefield (1984) and SMP1 (CISCAG, 2009). The decrease in carbonate beach sand fraction and increase in lithics and quartz fraction is shown in Fig 4. Landward transportation of marine carbonate beach material is also facilitated on the north Cornish coast by the tidal reach in the Hayle and Camel estuaries (Merefield, 1982) and dune formation facilitated by predominantly westerly winds.

The mechanism for the production of these skeletal sands remains uncertain. In cliff-backed bays and coves contemporary intertidal erosion of littoral skeletal material is undoubtedly a factor in the production of shell sands. However, some of the calcareous sediment may be of offshore origin (see Figure 1) where tidal scouring and biological action at depth sustains carbonate secreting organisms, including coralline algae and foraminifera, thus adding to the calcareous skeletal sands and muds which are being tidally re-cycled between beach and shoal. The greatest accumulations of shelly sands are associated with the wide embayments in the rocky coastline of west and north Cornwall. Here off-shore sediments are tidally deposited on beaches towards the centre of the embayments which are often dune-backed. However, adjacent headlands tend to control wave energy, possibly through the development of residual current gyres, and their influence on sediments entrained in long shore tidal streams may lead to accumulation of sand banks and shoals close off-shore where ebb and flow currents fluctuate. Thus a cyclic regime of sediment dispersal and deposition and, in its train, shoreline evolution, is established.

The carbonate content of modern Cornish beach sands, principally from north Cornwall has historically been of interest, primarily for their importance to agriculture (De La Beche, 1839; Karkeek, 1846). In the 13th Century the application of $CaCO_3$–rich beach sands was legalised (Isham, 2000), when Richard, Earl of Cornwall, gave local inhabitants the right, endorsed by a royal charter of Henry III in 1261, to take sea sand in order to improve the fertility of their land. Presumably the practice had predated this, and continued into the 20th Century in some areas. In the 16th Century, because of the deficiency in lime bearing rocks in Cornwall, the use of shell sand and pulverised maërl (see off-shore carbonates section) was supplemented by the importation of limestone from South Wales and the Plymouth area for processing. Significantly most of the surviving limestone kilns lie on the south coast of Cornwall (Isham, 2000). As such the use of lime on the land is of at least a millennium in duration and may be relevant to coastal tufa studies.

Beachrock

The cluster of indurated carbonate cemented beachrocks between Trevose Head and Pentire Point on the north Cornwall coast (in Mother Ivey's Bay, Harlyn Bay, on Rock Beach and in Daymer Bay in the Camel Estuary), has been described by Clarke, (1968), West (1970) and Howie (2009). Beachrock deposits are rare in the UK; other reported occurrences include Branscombe Mouth, Devon (West, 1970), Porth Neigl, North Wales (West 1972) and North Uist, Scotland (Kneale and Viles, 2000). Studies indicate that the Cornish beachrocks are essentially inter-tidal deposits, associated with high-carbonate beach sands. They are lithologically and mineralogically comparable to their present beach setting, and occur on beaches backed by high-carbonate content Holocene dunes. The mineralogy of the Mother Ivey's Bay and Harlyn beachrock indicates some loss of aragonite compared to the modern beach sand, and cementation, in an open system, by at least one phase of low-Mg calcite - possibly in fluids originating from nearby meteoric dune dissolution (West, 1970). The extent of the sea water/meteoric water interface in the process is unclear at present (Howie, 2009). Recent sand and gravel cementation is seen on present day beaches at the foot of a number of tufa seeps (Howie and Ealey, 2009) but on a very much smaller scale than the beachrock developments.

Dune sands

The inventory of low-lying coastal dunes, which total ~13 km^2 (1225 ha) in Cornwall, is relatively complete as a result of studies by DEFRA (2007). Those dunes with $CaCO_3$ content greater than 35% are indicated on the map (Figure 1) and their sand fraction carbonate is shown graphically in Figure 4. The majority of the carbonate-rich dunes are on the north and west coasts of Cornwall and most are transgressive, and are associated with high carbonate content beaches. These dunes have by far the highest $CaCO_3$ content (up to 70%; average ~50%) of all dunes in England and Wales (DEFRA, 2007, Table 3.10; maximum %CaO content recalculated to give %$CaCO_3$ content used in this review) and are comparable with the high carbonate content dunes on the Scottish Islands (May and Hansom, 2003). Dunes on the south Cornwall coast are much smaller (total ~70 ha), fewer in number and confined to Marazion, Praa Sands, Gunwalloe Church and Poldhu Coves, Kennack Sands and Par Sands, the largest of which are those at Gunwalloe Church Cove (46 ha). The dunes on the south coast have a lower $CaCO_3$ content (up to 50%; averaging ~25%) (DEFRA, 2007, Table 3.10).

Little work has been undertaken on the chronology, geology and hydrogeology of these carbonate dunes although the majority are designated Sites of Special Scientific Interest (SSSIs) primarily on their biodiversity. Based on data limited to dunes near Padstow (St Minver) and St Ives (Upton Towan) Merefield (1989) concluded that dunes in south-west England have a similar mineralogy and geochemistry to their local shore/estuarine sands, i.e. the low-Mg + high-Mg calcite to aragonite ratios are broadly similar but the aragonite values increase with decreasing particle size and also away from the coast, probably through protection afforded by soil chemistry. It is axiomatic that as the Holocene dunes migrated landward during the Flandrian transgression, the first dune sands affected the headland slopes bounding the bays before reaching their current inland position (May and Hansom, 2003). Carbonate cemented deposits at the base of dunes at the interface with underlying head have been observed at Sennen, Perranporth and Hayle (Mexico Towans) and are described as eolianites by West (1970) at Daymer Bay.

Tufa and speleothems

Borlase (1758) described the *"stillatitious productions of a sparry kind"* in caves near the Holy well in the parish of St Cuthbert, including in his account details of the nature of the stalactites, the *"fluor"* and *"alabaster"* covering cave walls and floors and a suggestion that the source of efflorescences may the *"sparry juices"* draining through the land. Intriguingly Borlase indicates that the thicker layers of *"alabaster"* from the caves may have been used for making jars. Thereafter, little reference to the Holywell speleothems is made, and little information on tufa in Cornwall is recorded in the literature other than brief records of tufa by Reid and Scrivenor (1906) and Reid (1907), and observations by West (1970, 1973) who concluded that the algal tufa deposits on modern cliff faces resulted from carbonate saturated or super-saturated meteoric run off from calcareous dunes.

A review by Howie and Ealey (2009) drew attention to the widespread distribution and variety of tufa in north and west Cornwall and the occurrence of speleothems in caves at Holywell Bay on the north Cornwall coast. Since the 2009 review the number of identified occurrences of coastal tufa and speleothems has more than doubled and these are observed to be far more widely distributed (see Figure 2). With one exception, at Nare Point on the Lizard Peninsula, the speleothems observed to date are seen to be associated with tufa occurrences and are therefore probably related in origin. The extent to which these tufa and speleothem deposits are linked to calcareous dunes is unresolved at present, but in some localities on the north Cornwall coast this is virtually certain (Howie and Ealey, 2009).

Pleistocene raised beach and dunes

Carbonate cemented gravels, littoral and dune sands, (the latter referred to locally as sandrock), are confined to late Pleistocene raised beaches at Trebetherwick, two sites in Fistral Bay and Godrevy on the north Cornwall coast. Sandrocks were used as an important local building material as early as the 14th Century (Bristow, 2001) and was employed as a freestone in buildings around Gwithian and Newquay and in churches, for example, at Crantock. Borlase (1758) recognised that around Newquay *"there is spar suspended in the waters of our northern coast which cemented these sands into stone"* and Paris (1818) was one of the first to draw attention to the recent formation of these sandstones stating that between St Ives and Padstow *"we actually detect Nature at work in changing calcareous sand into stone"*.

Unlike other Pleistocene carbonate cemented raised beaches, e.g. on the Gower Peninsula (West, 1970) and in south Devon (Campbell *et al*.,1998) the north Cornwall and north Devon (Croyde and Saunton) raised beaches do not rest on limestone bedrock and are overlain by non-calcareous head. Late stage temperate interglacial deposition of high carbonate content shell and dune sands, buried during subsequent glacial and periglacial phases, permitted cementation in stages, initially by the action of cold CO_2-rich meteoric water dissolving bioclastic aragonite and high-Mg calcite and re-precipitating $CaCO_3$ as sparry low-Mg calcite cement around mineral sand grains (West, 1973). Late stage solutional erosion and further carbonate cementation led to the development of palaeokarst piping (see Pazdur *et al*., 1995). As a result of this research, which has concentrated mainly on the Quaternary stratigraphy, age, trace fossils and palaeokarst piping, Godrevy and Trebetherwick have become Geoconservation Review Sites (Campbell *et al*., 1998) and both sites at Fistral are now designated as Regionally Important Geomorphological /Geological Sites (RIGS), currently known in Cornwall as County Geological Sites.

These raised beach deposits, without exception, occur on headlands. Those at Fistral and Godrevy flank bays, the centre of which is occupied by extensive younger Holocene dune deposits. Merefield (1984) also noted the highest carbonate concentrations in modern beach sands where local cliff lithologies are resistant to weathering and rocky intertidal zones permit large accumulations of skeletal invertebrates.

OFFSHORE CARBONATES

The Upper Cretaceous Chalk crops out on the sea bed in a broad swath 20-75 km off the Cornish coast from the Plymouth Bay Basin westwards to the St Mary's Basin, north across the Cornubian Platform and towards the South Celtic Sea where it is flanked by Eocene and Neogene limestones (Jones and Cockburn formations) which presumably once covered it (Figure 3). The proximity of a source of calcium for benthic biogeochemical recycling was thus probably established by the time the series of uplifts, transgressions and regressions commenced in the NE Atlantic and this is reflected by the successive limestones and other calcareous sediments of biogenic origin deposited offshore in the South Celtic Sea, the Western Approaches Trough and the Western English Channel (Evans, 1990) during the much warmer (compared to today) conditions from the Danian through to the Miocene. This 'carbonate factory' scenario, perhaps analogous to the modern carbonate factories and ramps seen in tropical to warm temperate seas, persisted well into the Pliocene.

During the late Quaternary, following the Devensian – Flandrian Transgression, an extensive layer (up to 1 m thick), of calcareous coarse sand and shelly gravel, in places more than 80% $CaCO_3$, was deposited on the sea bed and continues to be reworked (Evans 1990). Figure 1 shows the current extent and percentage of $CaCO_3$ in the off-shore sand fraction around Cornwall. Some of this material is of Pleistocene age (Stride *et al*., 1999; Reynaud *et al*., 1999; Danukalova and Lefort, 2009) although most appears to be Flandrian or younger. There is increasing evidence that this calcareous repository is being biologically recycled in the Channel and the Western Approaches (Larsonneur *et al*., 1982; Henrich *et al*., 1995; Wehrmann, 1998). The western part of the channel is *"considered to be abnormally rich in recent carbonate deposits, principally of biogenic origin"* (Davout *et al*., 2009) indicating that during the present interglacial, intense recycling of carbon and calcium, as calcium carbonate, by shallow shelf-dwelling nanno- and macro-organisms is underway. The level of biogenic carbonate production in temperate benthic zones such as the western Channel may be (pro-rata) of *"the same magnitude as the estimates for the average calcification of an entire coral reef"* (Gattuso *et al*., 1998).

The reef-like maërl beds off the coasts of S Cornwall and Brittany are probably part of this scenario. Maërl consists of sea-floor accumulation of the high-Mg calcite-rich exoskeletal nodules of once free-swimming coralline red algae *Phymatolithon calcareum, Lithothamnion glaciale* and, possibly, *L. corallioides*. Recognised by Ray in 1690 as *"Corallium album pumilum nostras. Small white coral. .... It is found plentifully in the ouze dredged out of Falmouth Haven to manure their lands in Cornwal"* (see Birkett *et al*., 1998) and described by Borlase (1758), who observed in Falmouth Harbour *"where there was such plenty of coral, a substance little different from the nature of spar"* and *"coarse coral"* at Par near Fowey, the largest maërl beds in England have developed in the Fal and Helford estuaries (Farnham and Bishop, 1985; Davies and Sotheran, 1995). In Cornwall and elsewhere in Europe, pulverised maërl has been commercially exploited for use in agriculture as a soil conditioner and for the filtration of acidic drinking water. Maërl beds are under threat from dredging, changing sedimentation load, sea-level and climate change and pollution. A protected accretion of living maërl, 150 ha in extent, has developed on the St Mawes Bank. Deposits of sub-fossil maërl have been reported from the mouth of the Helford River, in other parts of Carrick Roads and in Falmouth Bay. Its sporadic occurrence from St Austell to Mounts Bay indicates that maërl may once have covered a much wider offshore area off south Cornwall (UK Marine SACs, 2001).

DISCUSSION AND CONCLUSIONS

The Late Pleistocene to Holocene sands and gravels (Evans, 1990), covering the Devonian/Carboniferous bedrock in the 30 km coastal shelf around the Cornish coast are well-mixed with carbonate skeletal material with *"a high preservation potential under present conditions, despite the evidence of bioerosion, disturbance by storm waves and transport of material by currents"* (Stride *et al*., 1999) and are undoubtedly subject to entrainment in the strong tidal pulses prevalent around the south-west UK peninsula. Farrow and Fyfe (1988) considered that much of the north-west European shelf *"represents a modern-day equivalent of the 'calcareous shale' facies common in the geological record"* with the mud fraction of Holocene sediments on the shelf containing in the region of 10–20% $CaCO_3$ rising to over 50% $CaCO_3$ on supratidal mud-flats. The availability of calcium and carbon would therefore tend to sustain the production of shelly biota, the remnants of which are undoubtedly subsequently deposited and recycled on a large number of beaches around the Cornish coast as high-calcium carbonate skeletal shell sands. These sediments lie adjacent to a number of beaches, many of which are composed extensively of calcareous shell sand. These are, in turn, closely associated with carbonate dune fields, beachrock, tufa and, in coastal caves, speleothems. The available evidence indicates that these sediments and deposits have developed where there appears to be no association with limestone bedrock or calcareous head and therefore may be causally interrelated.

The possible effect of a north-east Atlantic influenced carbonate cycle in operation during the Pleistocene (Marine Isotope Stage 7 and/or 5e) is suggested by the occurrence of calcareous littoral and dune deposits around exposed headlands along the north and west Cornwall coast and north Devon coast (West, 1973; Gilbert, 1996) where mainland limestones do not occur. In contrast, the Quaternary calcareous raised beaches, cemented sands and tufas along the south Devon and south-west coasts of Wales are associated with limestone bedrocks and carbonate-rich head deposits which may have influenced their diagenesis (West 1970, 1973).

Fossil calcareous maërl accumulations are known from sediments of Miocene to Recent age on continental shelves and are used as stratigraphic markers and indicators of palaeoenvironmental conditions (Foster, 2001). The calcareous endoskeleton of the living algae forms annual growth bands similar to tree rings which make maërl a potential palaeoclimate proxy utilising, for example, Mg/Ca ratios in the individual growth bands. Maërl deposits from north France, Norway, Scotland and Ireland have produced useful on, for example Holocene climatic changes (Freiwald *et al*; 1991). The palaeoclimatological potential of maërl from Cornwall has not been studied in any detail.

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